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ELADINE: sensor monitoring and numerical model approach for composite material wing box shape distortions prediction

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Abstract. Out-of-Autoclave technologies are emerging as cost-effective alternatives to autoclave cure prepreg. However, their implementation in aerospace industry is still presenting many challenges. A common problem is the shape distortions that results in geometry mismatches with the tool. A way to avoid this and ensure a good final quality part is identifying the mechanisms that induce these deformations and optimize the manufacturing process of each component with the aim of reducing the production of faulty parts. The main objective of ELADINE project is to provide a method for shape distortions prediction on composite integral structures using an experimental-numerical approach. Different manufacturing parameters were monitored using Fiber Bragg Grating (FBG) sensors and DC-dielectric (DC) sensors and the resulting part geometry was examined by means of 3D coordinate analysis. The study performed for LRI (Liquid Resin Infusion) manufactured parts and the scenarios considered for the calibration of a Finite Element Method (FEM) based simulation tool are presented in the article. The resulting model will be implemented in a sub-scale demonstrator and, eventually, in a full 7-meter composite wing-box.

1. Background

Liquid Resin Infusion (LRI) is gaining more and more importance as an Out-of-Autoclave (OoA) alternative manufacturing technique to traditional pre-impregnated (pre-preg) fabrics [1]. Shape distortions are a common problem in the manufacturing of composite parts. A non-uniform distribution of the residual stresses generated during the manufacturing phase results in parts with different geometry than the tool (warpage of flat parts and spring-in of curved parts) [1]. These differences may result in components that do not meet the strict tolerances required in the assembly phase, leading to the rejection of such parts. Thus, understanding the origin of these residual stresses is key to optimize the manufacturing process, the quality of the final part and reduce the production of scrap parts. The research in this field has been focused on studying cure behaviour and post-manufacturing process quality assessment, aiming to optimize its production and reduce costs. The main mechanisms causing shape distortions are thermal anisotropy, resin polymerization shrinkage, tool-part interaction, resin flow and compaction and temperature gradients [1][2]. An effective way of understanding the magnitude of these effects on the manufacturing stages is monitoring key process parameters. Fiber Optic Sensor (FOS) are

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widely used in industrial application due to their minimal invasiveness and robustness to withstand harsh environments. Among FOS, Fiber Bragg Gratings (FBG) present a mature and cost-effective option for measuring parameters such as strain (ϵ) and temperature (T). These sensors are reflectors, with a periodical morphological change in the optical fiber's core that reflects a portion of the incoming light at a specific wavelength (Bragg wavelength), the rest of the light passes through without any property alteration. The Bragg wavelength (λ_B) is dependent on the refractive index (n_{eff}) and the grating period (Λ), as indicated in equation (1). When the fiber is subjected to external changes, there is a shift in the Bragg wavelength. The FBG can be calibrated to indirectly measure strain and temperature. In order to decouple these signals, the fiber can be encapsulated in a steel or silica capillary tube so that strain is not transmitted to the fiber and the wavelength shift is only due to temperature variations. T and ϵ signals can be decoupled using equation (2) [2][3].

$$\lambda_B = 2 \, n_{eff} \Lambda \tag{1}$$

$$\Delta \lambda_B / \lambda_B = (1 - P) \Delta \varepsilon_1 + (\alpha_n + \alpha_f) \Delta T$$
⁽²⁾

Regarding resin behaviour, dielectric analysis can be used for resin cure monitoring during the curing cycle. The working principle of dielectric (DC) sensors is based on the presence of dipoles on the uncured resin monomers that are oriented in the direction of an applied electric field conducting electricity. At the beginning of cure reaction, the resin is liquid, and its monomers can move freely. As the curing reaction proceeds, the monomers form polymeric chains in a rapid kinetically controlled reaction. With the formation of longer chains the mobility of the dipoles is restricted and the electrical resistance increases. When the gel point is reached, a complex network has formed and cross-linking of the polymeric chains takes places hindering the mobility of the polymeric chains. From this point, the reaction cure reaction is diffusion controlled (meaning the rate of reaction is significantly reduced) and the electrical resistance stabilizes marking the end of the cure reaction [4]. Thus, DC sensors indirectly measure resin cure evolution through resistivity. However, in order to quantify the degree of cure, thermal analysis can be performed to correlate the degree of cure percentage to the resistivity.

ELADINE project aims to understand and quantify the key manufacturing parameters that cause shape distortions on composite coupons using an integrated numerical-experimental approach. The manufacturing process was accurately monitored by combining FBG and DC sensors and the data gathered was used for the calibration of a FEM simulation tool for shape distortion prediction on large integral composite wing structures. This article covers the preliminary results of shape distortions predicted on coupons manufactured by LRI.

2. Methods

Small scale coupons were manufactured on the first stage of the experimental evaluation. A rectangular coupon with constant radius of curvature along the Y direction coupon of size 200x280mm and a C-shaped coupon of 200x100x50mm of were selected as study cases since they resemble sections of the skin and the spar, respectively, components of an aircraft wing-box.

2.1. Materials and manufacturing procedure for LRI

Carbon fiber (CF) preforms manufactured with HiTape dry fiber (Hexcel) by automated fiber placement (AFP) were used as reinforcement material. Hexflow RTM6 (Hexcel) epoxy resin mixed and degassed according to manufacturer indications was used as polymer matrix. The parts were produced using vacuum infusion, following the steps described on Figure 1.

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Figure 1. Experimental procedure performed with skin and C-spar coupons.

2.2. Monitoring manufacturing and shape distortions analysis

Before manufacturing, FBG and DC sensors were placed on the surface of the reinforcement material to monitor temperature, strain, and resin resistivity during manufacturing. Figure 2, shows a scheme of the sensor's location on each coupon geometry. The FBG sensors were positioned in three arrays (A, B and C) of five sensors (S1 to S5). The same distribution was placed on both surfaces of the laminate: the one in contact with the tool (below) and the surface in contact with the infusion consumables (above). No sensors were placed between layers to avoid damage of the previously consolidated laminate. Additionally, two DC sensors were positioned near the resin inlet and near the vent for in-plane impregnation monitoring. Composite tools were used for shaping and manufacturing to reduce part/tool interaction during cooling. Finally, shape distortions of manufactured coupons were analysed by a 3D coordinate measurement machine (CMM) and FBG sensors monitoring residual stresses. It is important to remark that these FBG sensors were the same ones used during the manufacturing phase which were kept intact after the demoulding process. The advantage of using the same sensors was that they were well embedded in the material.



Figure 2. Left: sensor distribution on skin coupons: FBG sensors (green dots) and DC sensor (square). Right: Sensor distribution on C-spar coupons: FBG sensor (red dots).

2.3. Numerical model

The purpose of this model is to create a Numerical Tool to be used for studying geometrical distortion phenomena during the curing process in a composite part. The code used was MSC Marc for solver and MSC Mentat for pre and post processing the data and the results. The numerical model was based on the CAD geometry and had the same dimensions as the CAD model. 3D solid composite hex8 elements were used for developing the model (element type according Marc classification: 149). Due to the

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necessity of balancing the number of elements and the time to run the nonlinear thermal structural model, a relatively small number of elements were kept for the model:10316 elements and 14201 nodes. Even so, the time to run the model was 1-2 hours on a 12 processors computer.



Figure 3. Composite tool, scanned tools and elements type used on FEM model

In modelling a composite material, the advantage of using the specified element type (149) is that the thickness of the element can be split in layers. Each layer can simulate a composite ply with a specific orthotropic material, a specific thickness, and a specific material orientation. From numerical point of view, for a better precision, even a single element, each added layer has an integration point. Still, to obtain a better precision, the coupon thickness was split in several layers of 149 type elements as presented Figure 3. Doing this, it was possible to obtain data regarding the gradients inside the thickness of the coupon model placed on the tool: curing degree gradient, temperature gradient, stress and strain gradients.

From the point of view of the successively applied loads and boundary condition, the run was divided into several virtual time segments. In the first run virtual time segment were applied: structural conditions like contact tool-coupon, vacuum bag pressure and thermal conditions like thermal contact tool-coupon, free convection on the free surface of the coupon, free convection on the free surface of the tool. Also, initial conditions for temperature and degree of cure and time variable ambient temperature were applied. This first time run segment simulates the period in which the structure is heated and cooled. The second virtual run time segment simulates the removing the vacuum bag: the pressure is removed but still the contact between tool and coupon is kept. The third virtual run time segment simulates extracting the part from the tool by removing all the contacts.

The Numerical Model is a transient one. This means that the model is solved iteratively. Each iteration describes the state of the model at a specific moment of time. The structure of the Finite Element Model, based on the way it was designed, can be applied to any kind of geometry and it can be described from two points of view: structural and functional components.

The Structural Components describe the structured data included in the model. The following components are identified: geometry and mesh, homogenized composite material ply properties defined for specific fibre volume fraction, material data and fibre orientation, contact definition and load and boundary conditions. Figure 4 presents in a figurative manner the connections between these components.



Figure 4. Structural Components connection in the numerical model.

Regarding the model's functional components, Figure 5 shows the data flow for the calculation of the distortion residual stresses. All the Functional Components of the Model are connected. At each time

increment, the data is transferred from a Functional Component to another. The Functional Components influence each other in a way that, at a specific time increment a Functional Component may transfer data to all the Functional Components in the model and may receive data from all the Functional Components in the model.



Figure 5. Functional Components Data Flow

3. Results

3.1. Experimental results

The left graph of Figure 6 shows the signals registered by a DC sensor (resistance) a FBG-T (temperature) and a FBG-S (strain) through the whole manufacturing cycle of a skin coupon. In this graph, only the response of one of each kind of sensors is shown to illustrate how different process parameters were monitored. In-plane impregnation was detected by DC sensors as a sudden drop on the resistance. Resin arrival was also sensed by the FBG-T as a decreased in temperature since resin and CF laminate were at different temperatures. The minimum viscosity of the resin corresponded to the lowest value of resistivity. Gel point was spotted by the inflexion point in the DC sensor curve and that point was also considered as the initial point for strain readings. From the gel point on, the resin starts developing mechanical properties and compressing the sensors that is negative values of strain which cause by resin cure shrinkage during the dwell phase and thermal contraction during the cooling stage.



Figure 6. Real time monitoring data of strain (green), temperature (blue) and resistivity (red) (left); and map of temperatures registered during resin infusion of a skin coupon (right).

Once the main events related to the curing cycle were identified on the sensor readings, more information was obtained considering the whole scheme distribution. The right graph on Figure 6 shows the temperature distribution during injection on a skin coupon in which the resin flow front was distinguished by the colder colours while the warmer colour corresponds to unwetted fiber. The

distribution of FBG-S sensors provided relevant information regarding the strain distribution across the coupon surfaces. The left graph of Figure 7 shows that after the gel point, the sensors located between tool and laminate (below) monitored less strain variation that those placed on above the laminate. This means that the residual stresses at the end of the curing cycle were of higher magnitude on the surface in contact with the vacuum bag. Moreover, a map of strain was extracted from the sensor reading at the end of the cycle just before demoulding (see right graph of Figure 7) which confirms the presence of an irregular strain distribution also in the same plane. These uneven distribution of residual stresses after the manufacturing cycle might be the cause behind shape distortions after demoulding.

In a comparison between Skin and C-spar coupons monitoring data, the same events were identified during monitoring the manufacturing phase regardless the geometry of the part. This makes sense since size of the dry fiber preform was very similar so that the infusion process takes the same time and impregnated similar amount of material, moreover in both geometries the arrays of FBG sensors were placed perpendicular to the resin flow front.



Figure 7. Strain variation during curing cycle (left) and strain distribution registered at the end of the curing cycle on the skin coupon surface in contact with the vacuum bag (right)

On the other hand, post-manufacturing analysis revealed that the shape of skin and C-spar coupons behaved differently. 3DCMM results showed that skin coupons were more curved after several days from demoulding (warmer colours on Figure 8 denotes increased of Z coordinate). Regarding shape distortions on C-spar coupons, the geometry of the coupon was compared with the tool geometry and the angle that forms the web (central flat part) and the flanges of the C-spar were also measured. Warpage of the web was detected on the 3D CMM measurements which results in spring-in of the flanges since a reduction in both angles was observed. This distortion was noticed by a reduction in the distance between the flanges (d), such distance was quantified on several points along the flange and compared to the same points on the tool. A significant reduction (1,5mm average) in this magnitude was found confirming the spring-in of the C-spar coupon (see Figure 9).



Figure 8. Plotted 3D CMM measurements contour plot of shape distortions evolution with time of skin coupon.

Regarding strain signal of the sensors that conserved their integrity after demoulding, the results obtained showed a high variation on the wavelength during the first days after demoulding. This change can be associated to a stress released accumulated during manufacturing. After that the strain did not

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stabilize but the remaining strain was not significant to cause macro distortions on the coupon. This occurs for both Skin and C-spar coupons (Figure 10).



Figure 9. Spring-in of a C-shaped coupon evaluated through distance between flanges of 3D CMM measured points compared with the tool.



Figure 10. Strain response monitored by sensors embedded in the center on surface in contact with the tool on skin coupon (left) and on a C-spar coupon (right)

3.2. Numerical tool calibration and results

To perform a comparison between the FEA distorted part and the experimental distorted part the several steps were done. First, a post-processing option is to export the FEA model of the distorted structure to obtain a CAD file from the numerical model. This way, a distorted CAD part model is obtained from the FEA model results. Secondly, the distorted experimental coupons were laser-scanned at high resolution. The result was a 3D model of the distorted experimental part. Finally, in a CAD environment (CATIA) were imported, superposed, and compared the three components: original undistorted CAD part, FEA distorted CAD part obtained as a result of the model run and experimental distorted CAD part obtained by scanning. The information obtained by this comparison was used for the numerical tool calibration. After an extended number of numerical simulations trials, employing different types of parameters. A final and most suited approach was selected for shape distortion predictions due to its good correlation with the experimental results. The model was analyzed after the resin infusion process and the initial parameters were an initial degree of cure of 0,7166% and 120°C of temperature. The friction coefficient was set in a range between 0,1 and 1.

After the calibration of the numerical model, the results for shape distortions on skin coupons were similar to the ones obtained experimentally. No longitudinal rolling was observed but rather an increase of the curvature of the skin, the maximum spring-in value obtained was 0,391mm. The measured distortions of the manufactured coupons were generally 8% to 12% greater than the numerically obtained values. The distortion pattern of the virtual coupon precisely resembles the pattern observable in the experimentally obtained coupons. From this point-of-view, the numerical model is able to accurately predict the deformation pattern and the order-of-magnitude of these deformations. Therefore, the results given by the numerical model are somewhat conservative. The 8% to 12% difference is comparable to the hundredth part of a millimetre; therefore, the results were deemed satisfactory for

most manufacturing-related applications. It is important to note the fact that same values and ranges apply for the C-spar deformations. While the skin coupon deformations were measured in millimetres (maximum deflection), the deformation for the C-shaped coupons were quantified in degrees – the web-cap angle of the tool vs the web-cap angle of the deformed part. The measured c-shaped coupons have performed spring-in for 1.4° - 1.6° for each cap. The numerical model predicted the spring-in would fall into the 1.25° - 1.55° range. The percentual difference between the manufactured coupon and the numerically modelled coupon is, on average, 10%, also conservative versus reality.



Figure 11 Numerical tool results after calibration for skin coupon (left) and C-spar coupon (right)

4. Conclusions

The numerical-experimental approach presented served for the development of a methodology for shape distortion analysis on composite parts manufactured by liquid resin infusion. The experimental approach was based on process monitoring with FBG and DC sensors. The first ones were capable of effectively monitor strain and temperature during manufacturing and post-manufacturing detecting resin arrival, temperature, and strain variations on different parts of the coupon. DC sensors detected the main events related to resin cure behaviour during (resin arrival, cure, and temperature evolution) the curing cycle. A FEM-based numerical model capable of working on different geometries was developed for prediction of shape distortions on complex structures. The experimental data collected from the sensors embedded on the coupons was used for calibration of the numerical tool. Both approaches predicted similar behaviour on the coupons studied: reduction of radius of curvature on skin coupons and springin of the caps the C-spar coupons. Moreover, this methodology was implemented in the manufacturing of composite with other materials such as oven cured prepreg (Toray P707AG-15 unidirectional), obtaining precise distortions predictions also for this material. Thus, it can be concluded that these two studies combined, provide a powerful tool to elucidate the mechanisms originating the postmanufacturing deformations of composite parts. Further work of calibration of the numerical tool will be performed by embedding sensors on more complex structures. This will provide a deep insight of the manufacturing process allowing optimization and reduction of the faulty parts.

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